In the News

Our final exam is scheduled for

THURSDAY, MAY 12, 5:20-7:20, room SAM 311

The format will be the same as for the midterm. The final will cover the entire semester

Cosmology

Cosmology: the study of the origin and evolution of the large-scale structure of the Universe and the geometry of spacetime, and the interactions between matter (baryonic or "normal" and non-baryonic or "dark") and energy (radiative energy of photons and quantum fluctuations or "vacuum energy")

Large Scale >> scale of superclusters (>1 Gpc)

The Cosmological Principle

The guiding principle of cosmology is that there is no preferred place in the Universe. This means

- the Universe must look homogeneous (the same at every location)
- the Universe must look isotropic (the same in every direction)

on sufficiently large scales.

The Hubble Flow

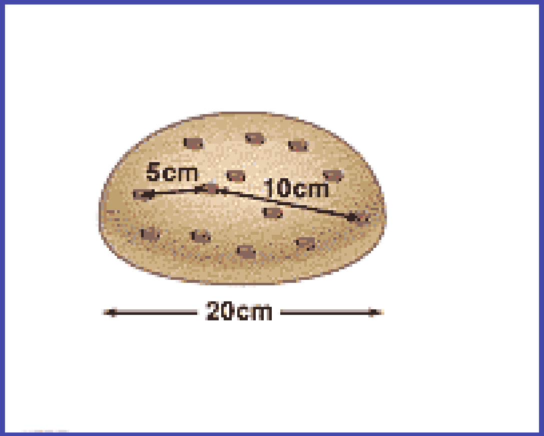
Slipher, Humason and Hubble (and others) showed that galaxies ("spiral nebulae") were (mostly) redshifted

Hubble derived the relation between redshift and distance to the nebulae:
$V=Hr$

As the Universe ages, the scale of the Universe increases.

("Scale of the Universe"~ average distance between galaxies)

At earlier times Universe must have been smaller.



The Big Bang

Corollary: if “size” of the Universe was smaller in the past, there must have been a finite origin of the Universe.

Abbe Georges LeMaitre (1927): “primordial atom”

Sir Fred Hoyle (~1948): coined the term “Big Bang” ... as an insult

Newtonian Cosmology

Consider a galaxy of mass m trying to escape from a Universe of mass M (escape where?). The galaxy's escape velocity is

$$1/2mv^2 = GMm/r$$

$$1/2v^2 = \frac{G(4\pi r^3 \rho_{crit})}{3r}$$

$$1/2(H_o r)^2 = \frac{G(4\pi r^3 \rho_{crit})}{3r}$$

$$\rho_{crit} = \frac{3H_o^2}{8\pi G}$$

So if

- $\rho > \rho_{crit}$, then test galaxy can't escape; "**Universe Bound**";
- $\rho < \rho_{crit}$, then the test galaxy "can escape"; "**Universe Unbound**"

Since $H_o = 71$ km s^{-1} Mpc^{-1} $= 2.3 \times 10^{-18}$ cm s^{-1} cm^{-1}, $\boldsymbol{\rho_{\mathrm{crit}} = 9.47 \times 10^{-30}}$.

Note that H=H(t): H_o is the value of H at the present epoch. H is spatially but not temporally constant

Relativistic Cosmology

Relativity shows that mass and energy are equivalent, and that matter (energy) curves space

Einstein's original "Field Equation" is

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

where the LHS is the spacetime curvature and the RHS is the source term (the energy momentum tensor)

The Friedmann Equations

A homogeneous and isotropic solution to Einstein's field equation yields the "Friedmann-Robertson-Walker" metric

$$ds^2 = -dt^2 + a^2(t)R_o^2[\frac{dr^2}{1-kr^2} + (rd\theta)^2 + (r\sin\theta d\phi)^2],$$

Using this metric the field equation reduces to the Friedmann Equations

$$H^2 \equiv (\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2R_o^2}$$ and $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

The Static Case

Einstein (1916): space velocities of stars << c; Universe static

=> $\dot{a} = 0, \ddot{a} = 0$

The field equation could yield a Universe with $\dot{a} = 0$

But these solutions were not stable ($\ddot{a} \neq 0$) since

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

and p>0 for normal matter

The Cosmological Constant

So Einstein showed that his field equation could be written

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

where Λ is known as the "Cosmological Constant"

Einstein's Blunder?
"I thought I made a mistake once...but I was wrong"

Einstein's Static Solution

After including the cosmological constant, the Friedmann equations can be written

$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2 R_o^2} + \frac{\Lambda c^2}{3}$$

and

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

which can have a solution with $\dot{a} = 0, \ddot{a} = 0$ and ρ, p and L all >0

Universe could be static…

Improbability of the Static State

- Darkness of the night sky suggests that the Universe is finite in space and time (“Olber’s paradox”)
- Newtonian gravitation suggests that a non-accelerating Universe is unstable
- Einstein’s static solution is not stable to perturbations
- Finally Hubble’s observations showed that the Universe at the present epoch is expanding

Critical solution

With $H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2 R_o^2} + \frac{\Lambda c^2}{3}$ setting the curvature term k=0 gives

the critical case, which can be written $\Omega_m + \Omega_\Lambda = 1$ where

$\Omega_m = \frac{\rho_m}{\rho_{crit}}$ is the ratio of the matter density to the critical density

$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{crit}}$ is the ratio of the "vacuum" energy density to the critical density

$\rho_\Lambda = \frac{\Lambda}{8\pi G}$ is the vacuum energy density ("Dark Energy")

$\rho_{crit} = \frac{3H^2}{8\pi G}$ is the critical density

Flat, Open, Closed

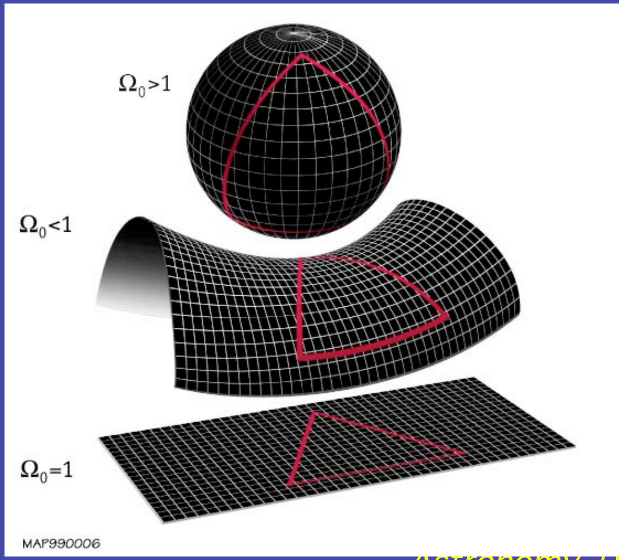
if $\Omega_m+\Omega_\Lambda = 1$, the universe is "flat"

if $\Omega_m+\Omega_\Lambda < 1$, the universe has negative curvature: Open

if $\Omega_m+\Omega_\Lambda > 1$, the universe has positive curvature: Closed

In an open or flat universe, the expansion of the universe continues forever. ("Big Rip"?)

In a Closed universe, the expansion is halted and the universe will recollapse ("Big Crunch")



Equations of State

for a given constituent (i) of the Universe, we can write

$$\rho_i = w_i p_i$$

where ρ_i is the energy density of the constituent and p_i is the pressure of the constituent

If energy and momentum are conserved then $\rho_i \propto a^{-n_i}$ and $n_i = 3(1+w_i)$

Component	n	w
matter	3	0
radiation	4	1/3
Dark energy	0?	-1?

Neutrinos

Abundance of neutrinos produced in early universe could have cosmological consequences if neutrinos have mass.

Neutrino mass constrained as $0.1eV<m_\nu<1eV$ =>

$1eV = 1.8x10^{-33}$ gm ~ $2x10^{-6}\ m_e$

If current density of ν = 100 cm-3,

then $\rho_\nu < 1.8x10^{-31}$ gm cm^{-3}

so $\Omega_\nu<0.01$

http://physicsweb.org/articles/world/11/7/3
http://cupp.oulu.fi/neutrino/nd-mass.html

Relics of the Big Bang

Early experiments at developing low-noise receivers to communicate with Echo satellite

Ohm (1961) finds excess of 22.2±2.2 K when 18.9±3K expected

TABLE II — SOURCES OF SYSTEM TEMPERATURE

Source	Temperature
Sky (at zenith)	2.30 ± 0.20°K
Horn antenna	2.00 ± 1.00°K
Waveguide (counter clockwise channel)	7.00 ± 0.65°K
Maser assembly	7.00 ± 1.00°K
Converter	0.60 ± 0.15°K
Predicted total system temperature	18.90 ± 3.00°K

the temperature was found to vary a few degrees from day to day, but the lowest temperature was consistently 22.2 ±2.2°K. By realistically assuming that all sources were then contributing their fair share (as is also tacitly assumed in Table II) it is possible to improve the over-all accuracy. The actual system temperature must be in the overlap region of the measured results and the total results of Table II, namely between 20 and 21.9°K. The most likely minimum system temperature was therefore

$$T_{system} = 21 \pm 1°K.*$$

The inference from this result is that the "+" temperature possibilities of Table II must predominate.

Fig. 8 An excerpt from E. A. Ohm's article on the Echo receiver showing that his system temperature was 3.3K higher than predicted

using a 20 foot "horn" antenna at Bell Labs in NJ

The 3K Background

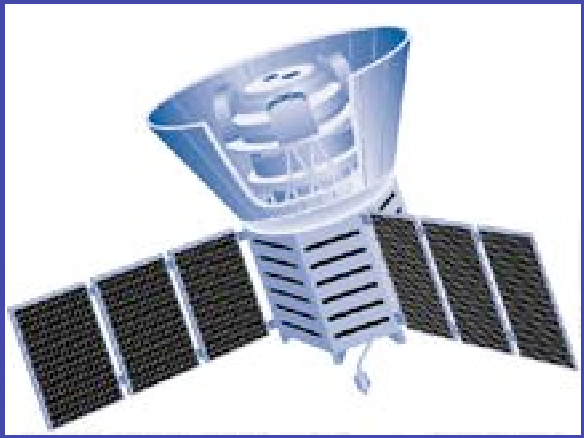
1965: Penzias & Wilson (using the same antenna, more accurately calibrated) find a 7.3±0.3 K temperature when a total of 4.2±0.7K expected: 3.1 K background

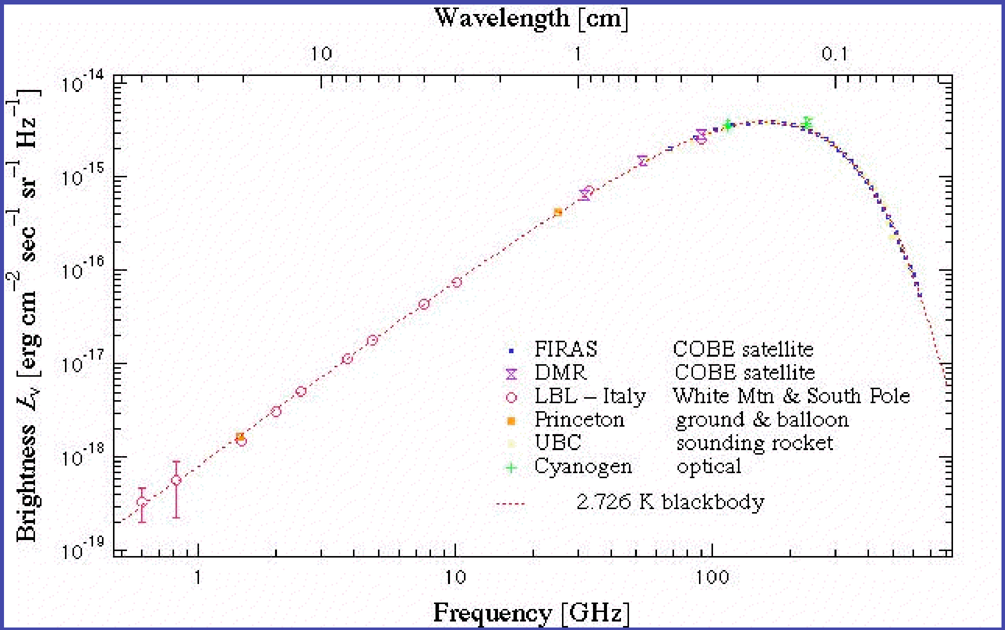
"...excess temperature is, within the limits of our observations, isotropic, unpolarized, and free of seasonal variations"

Dicke & Peebles at Princeton understand this as the relic background left over from a previous hot phase of the Universe

COBE

COsmic Background Explorer (COBE) provided the best measurement of the spectrum of the microwave background
T= 2.726K





Successes of Standard Big Bang Cosmology

The "Hot Big Bang" model in which Universe started from a hot, dense state which began to expand has a number of successful predictions/explanations:

- explains the observed ratio of H/He
- explains the observed expansion of the Universe
- explains the current temperature of the Universe

Problems with Standard Big Bang Cosmology

There are some things the Standard Big Bang model doesn't explain/address:

- non-uniformity of the microwave background: How does structure form?
- horizon problem: why are disconnected regions of the Universe so nearly the same?
- why is the Universe so nearly flat? Is it really flat?
- monopole problem: particle physics predicts creation of lots of monopoles during symmetry breaking in the early Universe, but no monopoles are seen.

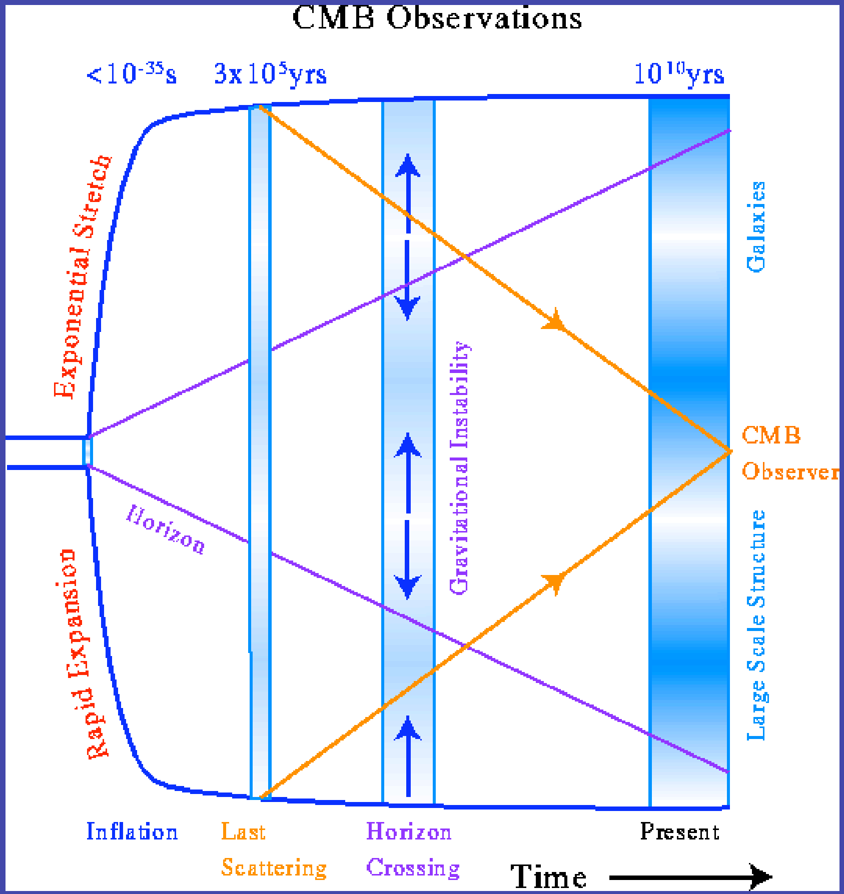
Inflation

Inflation postulates that the Universe experiences a period of exponential growth for some time interval - corresponds to a phase transition in the early Universe

During this exponential expansion

- curvature of the Universe expands: Universe looks flat
- density of monopoles drops
- fluctuations in the primordial density in the Universe should have the same power on all spatial scales

Inflation Schematic



Tiny Universe undergoes an epoch of exponential growth during which small inhomogeneities in density grow large and help form structure.

http://background.uchicago.edu/~whu/beginners/introduction.html

Supernovae Distances

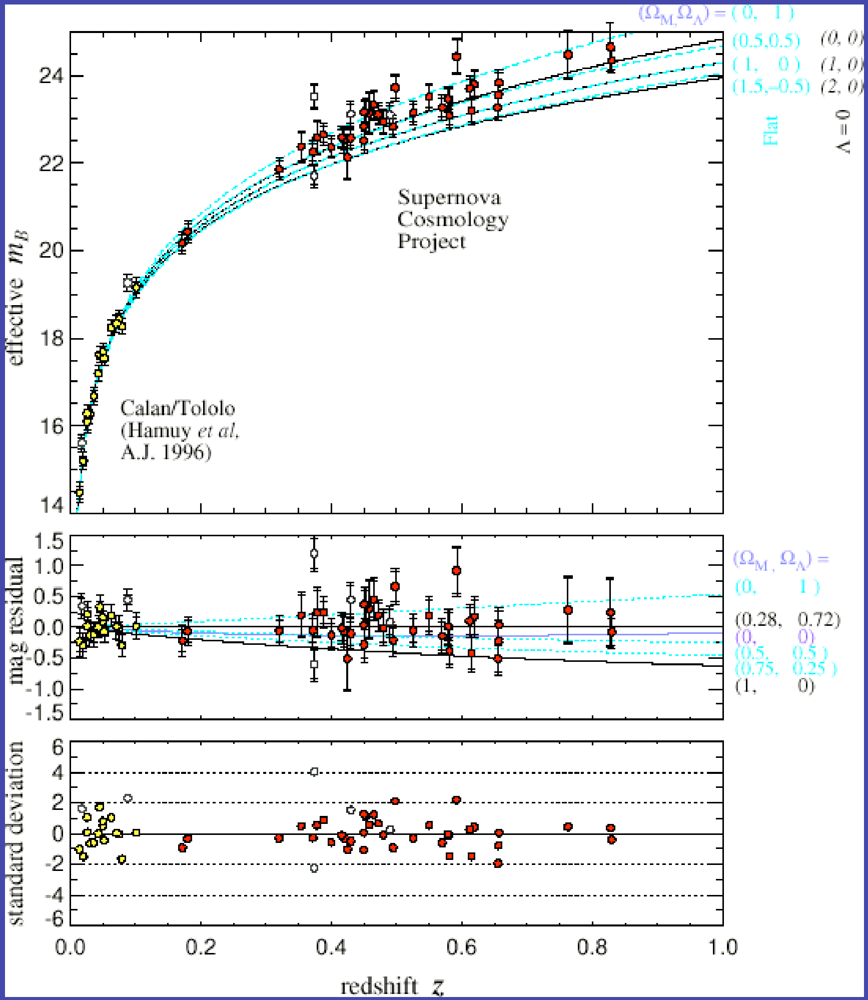
Availability of HST and large ground based telescopes allowed astronomers to detect supernovae in distant galaxies (out to $z \sim 1 \sim 2 \times 10^9$ pc)

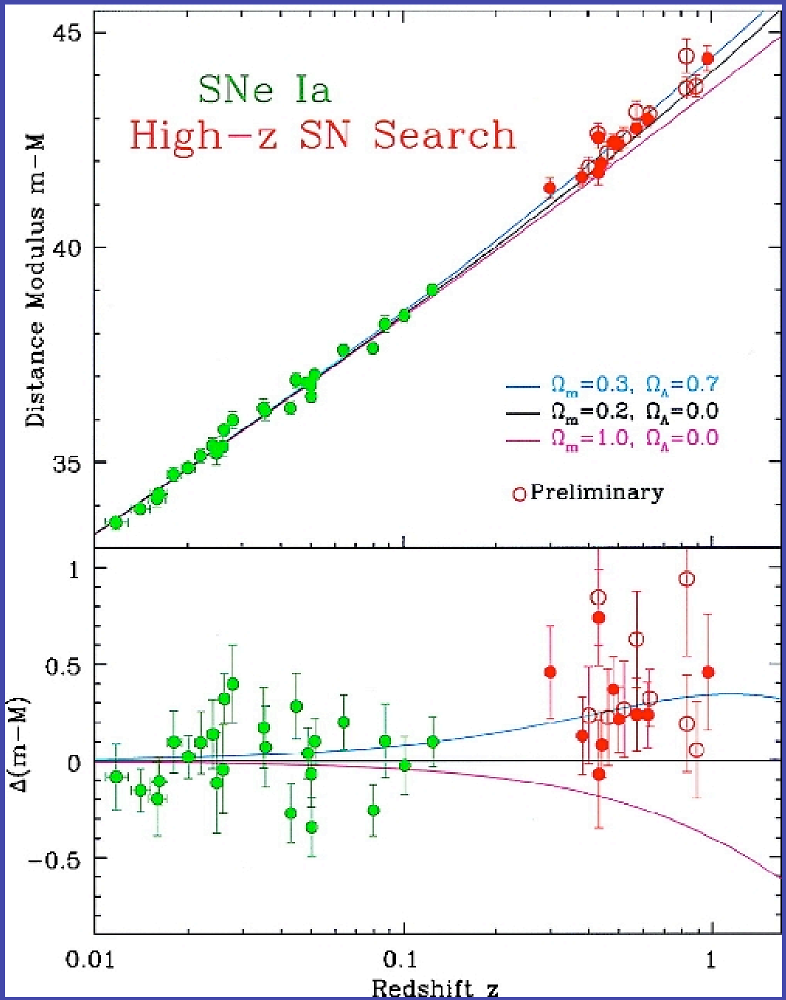
By identifying SN Ia, and assuming that these are standard candles, distance to the distant galaxy can be directly measured.

Can compare the distance as a function of redshift to see if it agrees with the Hubble flow

High-Z Supernovae:
http://cfa-www.harvard.edu/cfa/oir/Research/supernova/home.html
Supernovae Cosmology Project:
http://panisse.lbl.gov/

SNIa distance measurements





SNIa and the Accelerating Universe

Measurements of SNIa distances suggest that they appear fainter (farther away) than they should based on standard cosmology (with no cosmological constant)

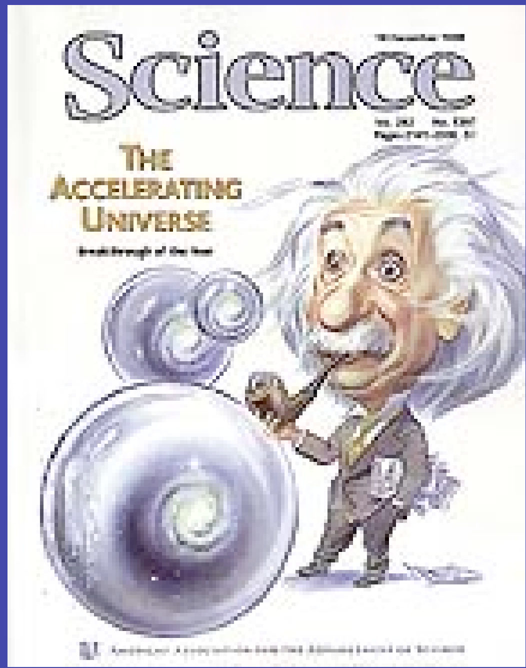
Universe not slowing: Accelerating!

Suggest $\Lambda \sim 0.6$

Caveats:

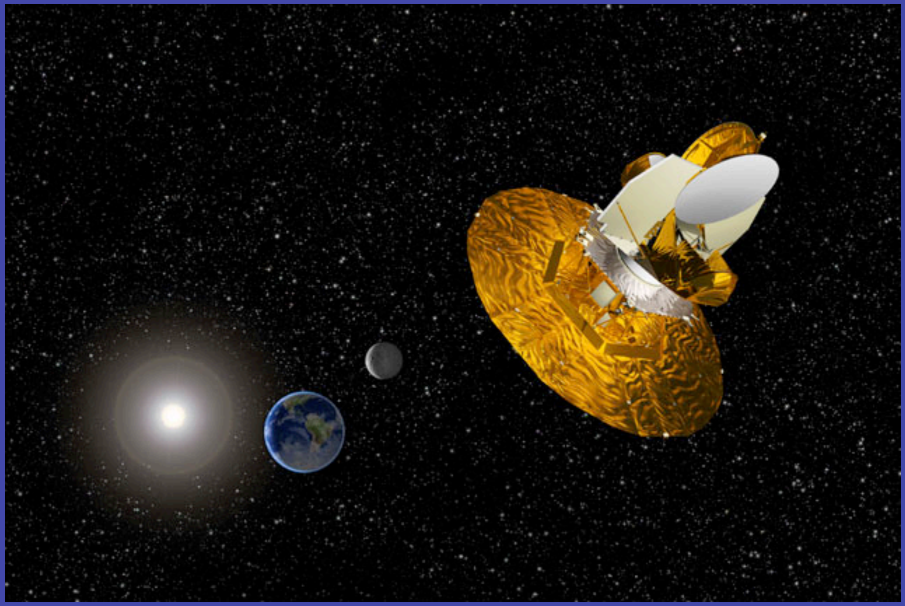
- are they really SNIa
- are they really standard candles even at high z?
- can absorption/dust be neglected?

All signs point to yes...

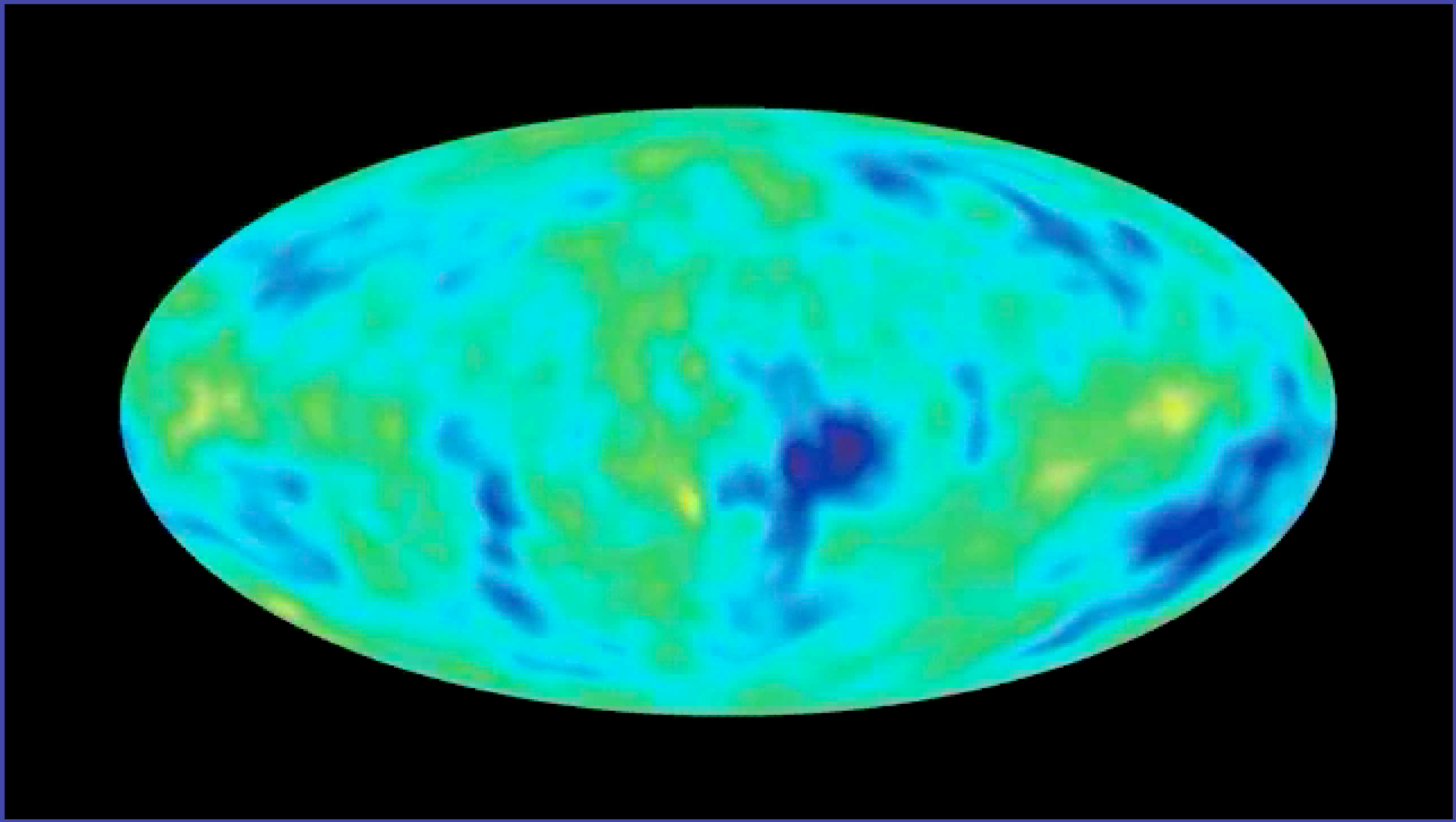


WMAP - Wilkinson Microwave Anisotropy Probe

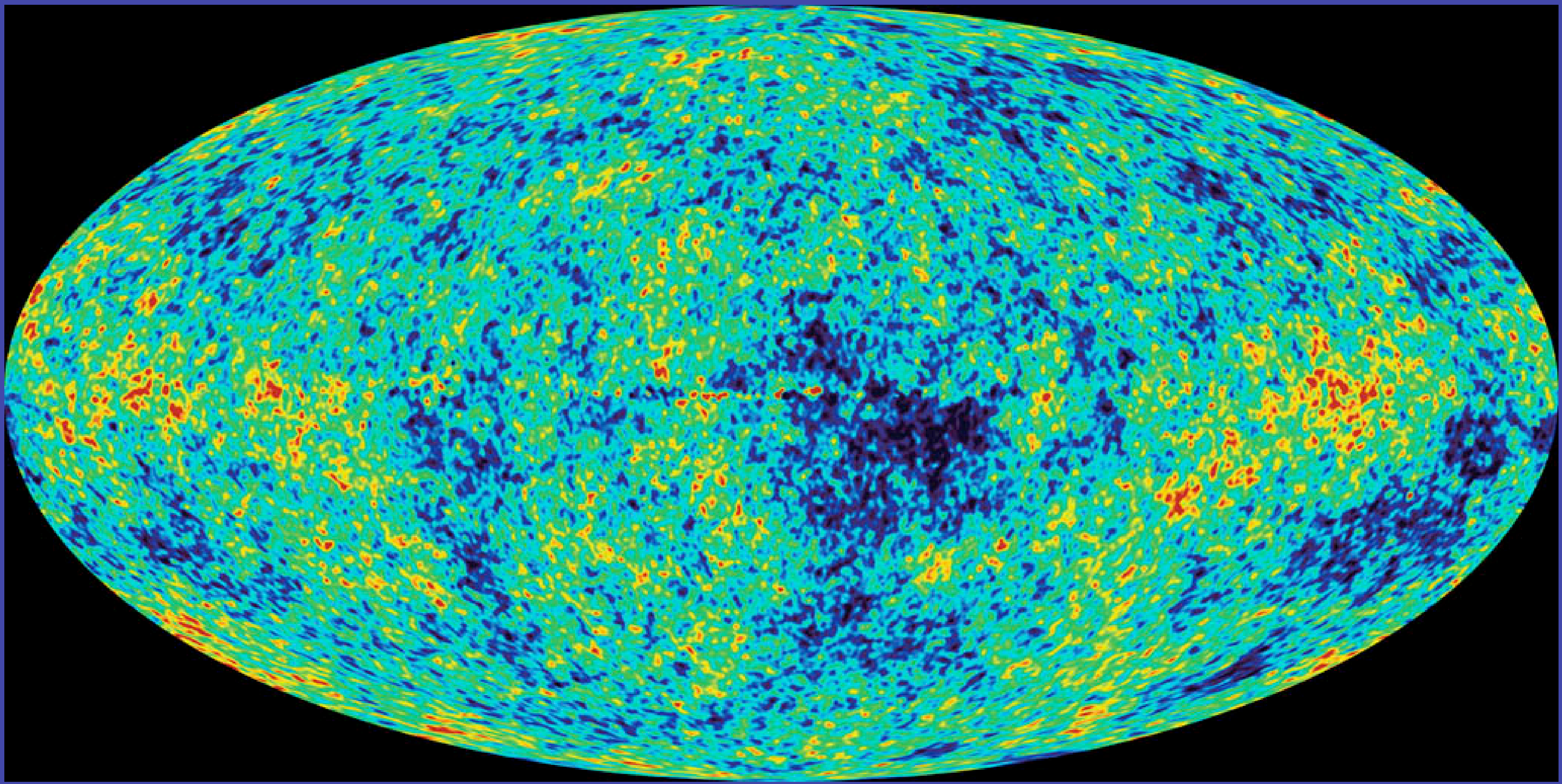
WMAP is a small satellite designed to make precise measurements of the temperature of the microwave background to measure the spatial variations of temperature/density in the early Universe.



WMAP vs. COBE



WMAP Temperature Anisotropies



cooler regions blue; hotter regions yellow-red
after removal of all foreground and other non-cosmological emission

Analysis of the Anisotropies

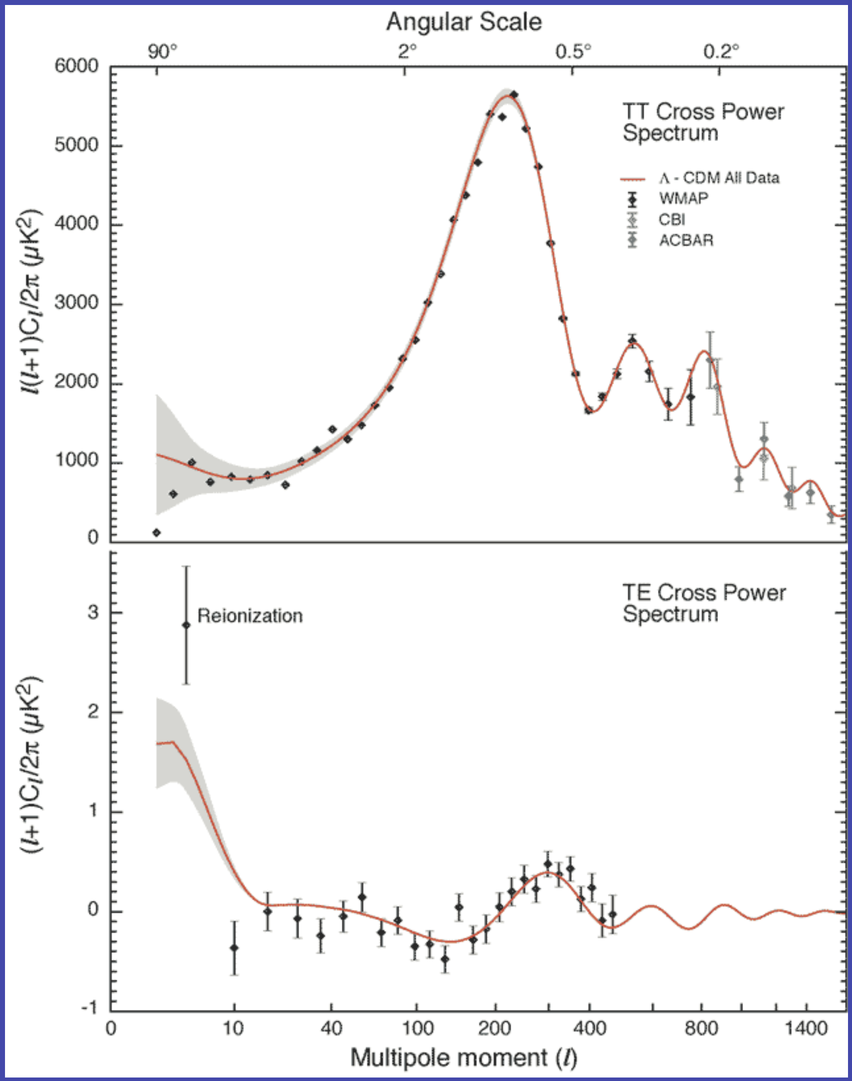
Different cosmological models (with different epochs of inflation, different Ω's, different mix of baryonic to dark matter, etc) will yield different set of anisotropies

The anisotropies can be characterized in a statistical sense as a series of spherical harmonics with different amplitudes for different modes ℓ

WMAP allows a direct determination of the power for each mode for a large number of modes, which allows precise determination of the cosmological model

For details see
Hinshaw et al., 2003, ApJS,, 148, 135, and
Verde et al., 2003, ApJS, 148, 195.

Harmonics of the Anisotropies



WMAP angular power spectrum agrees with cosmological constant, cold dark matter dominated model

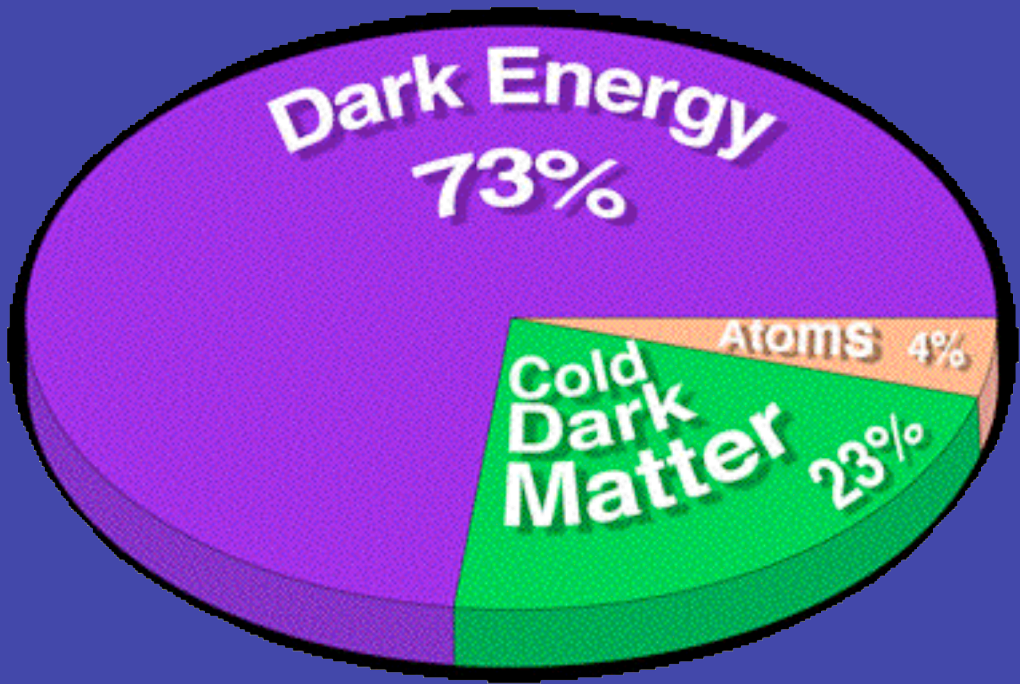
WMAP polarization shows that the epoch of re-ionization occurred (optical depth $\tau \sim 1$) at early times in the Universe.

WMAP results

By fitting the power spectrum of the anisotropies with different cosmological models, WMAP derives the following cosmological parameters:

Parameter	Value
H_o	71^{+4}_{-3}
Ω_b	0.04
Ω_m	0.268
Ω_ν	0.015
Ω_{tot}	1.02 ± 0.02
w_{DE}	<-0.78
Age of Universe	13.7 ± 0.2 Gyr

The WMAP Universe



In the WMAP universe, only 4% of the energy in the Universe is due to "normal" atoms

Dark Energy

Dark Energy seems to be related to the energy of empty space, the “vacuum energy”.

Unclear whether Dark Energy evolves with the Universe or not.

Measuring Vacuum Fluctuations

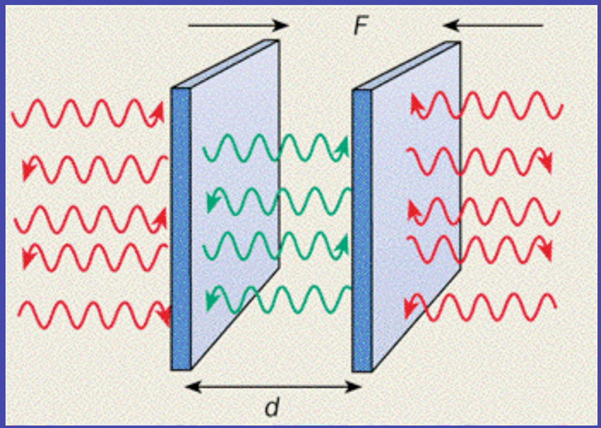
Vacuum energy can be directly measured via the "Casimir Effect"

Casimir Effect: two flat conducting plates separated by a distance d in vacuum have a force of attraction per unit area of

$$P_c = \frac{\hbar c \pi^2}{240 d^4}$$

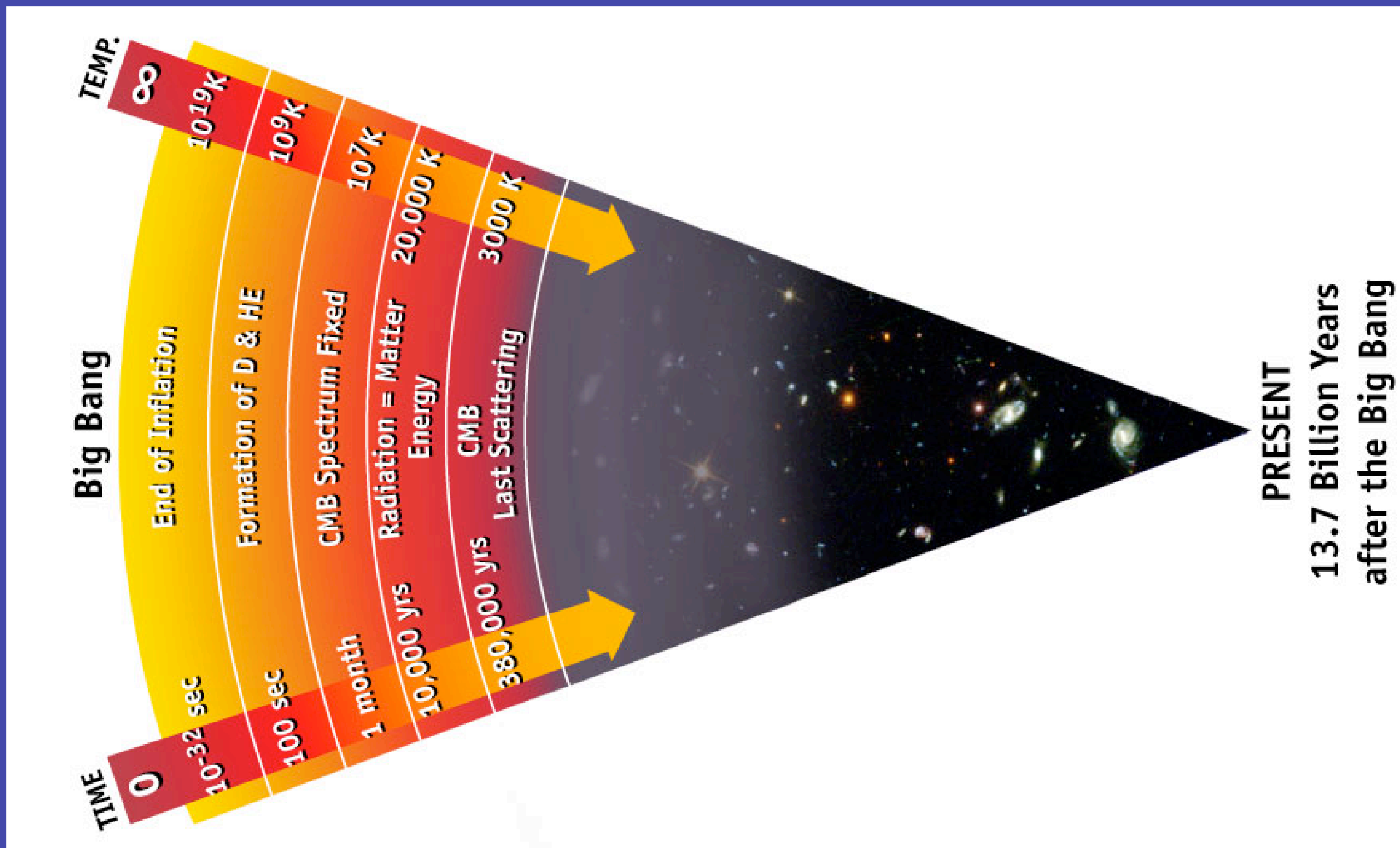
between them, due to vacuum energy fluctuations.

The Casimir effect is produced because quantum fluctuations which have a wavelength = Nd are amplified while other wavelength flucutations are suppressed. Although the amplified fluctuations push the plates apart, the suppressed fluctuations act like a stronger negative pressure which pushes the plates together.



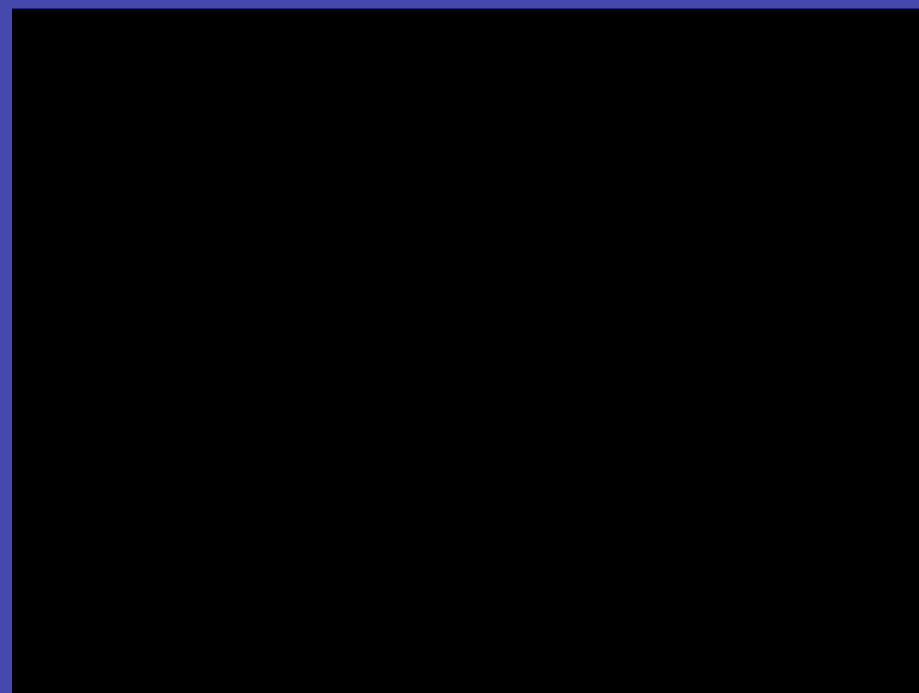
http://physicsweb.org/articles/world/15/9/6/1#pw1509061

The History of the Universe



Growth of Structure

from a nearly smooth collection of dark matter (and other stuff) structure (Superclusters, clusters, galaxies, stars) start to form



simulation from Andrey Kravtsov

http://background.uchicago.edu/~whu/beginners/introduction.html

The Dark Ages and re-ionization

at some point after the Big Bang the temperature of the Universe drops so that protons and electrons recombine to form neutral H.

By this time Cosmic Background photons shifted into the IR: Universe in a “Dark Age” (no visible light)

At some point the H in the Universe is re-ionized by

- the first stars
- the first AGN

The First Stars

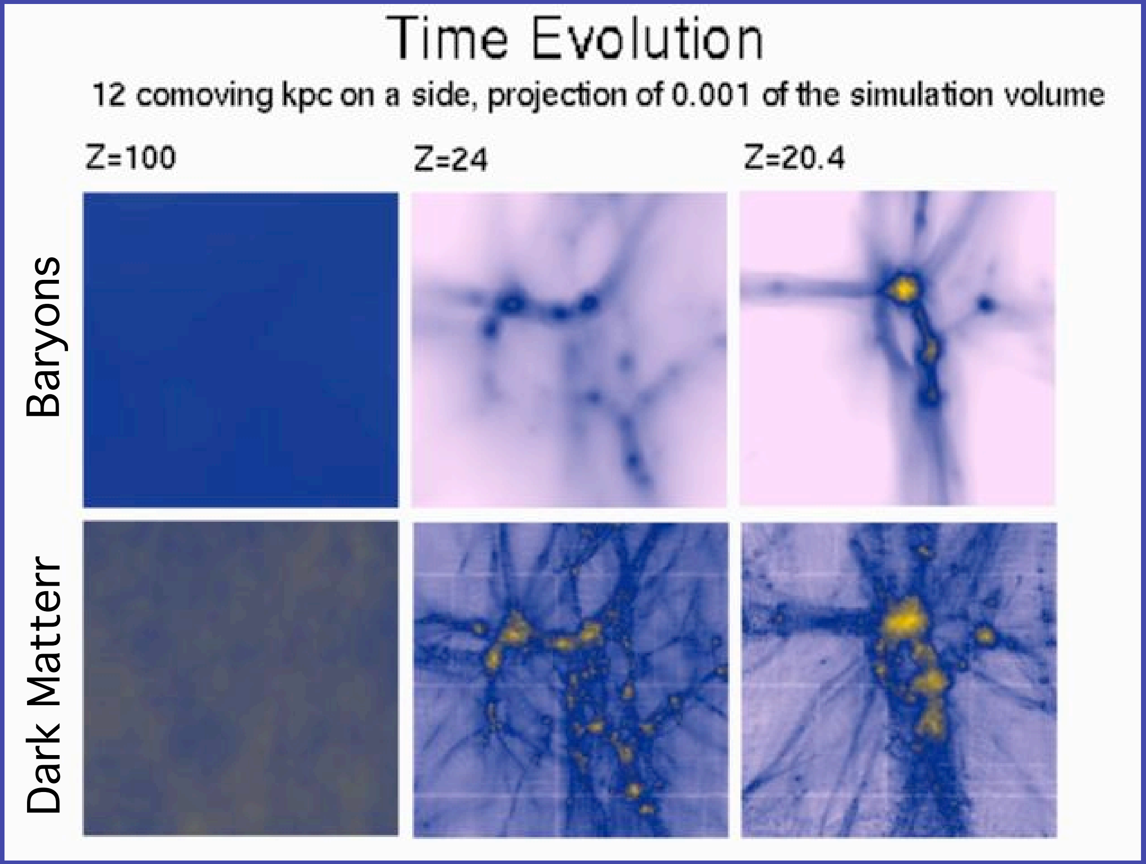
The first stars were Population III objects: only H and He

Stars should be very massive

First generation of stars provides:

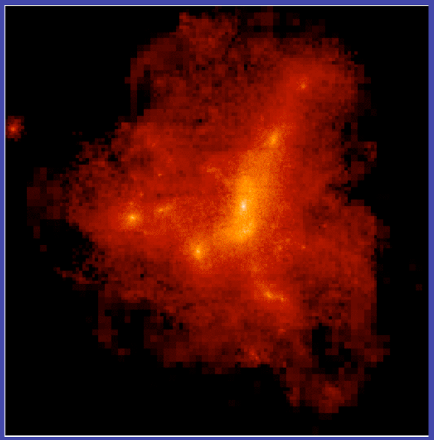
- UV to re-ionize Universe
- SNe to ionize and structure the Universe
- medium-mass black holes: seeds of AGN?
- heavy elements to pollute the Universe

Simulating Star formation



Numerical simulation of formation gravitational collapse in the early Universe to small scales

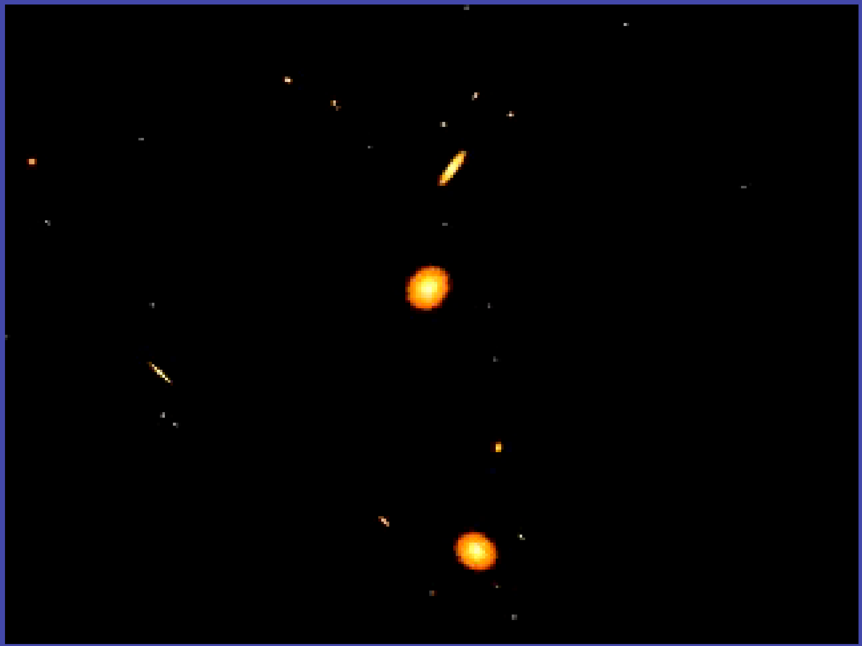
at about z=18 a collapsed, 10^8 MO object (a proto-galaxy) has formed a star in its center.



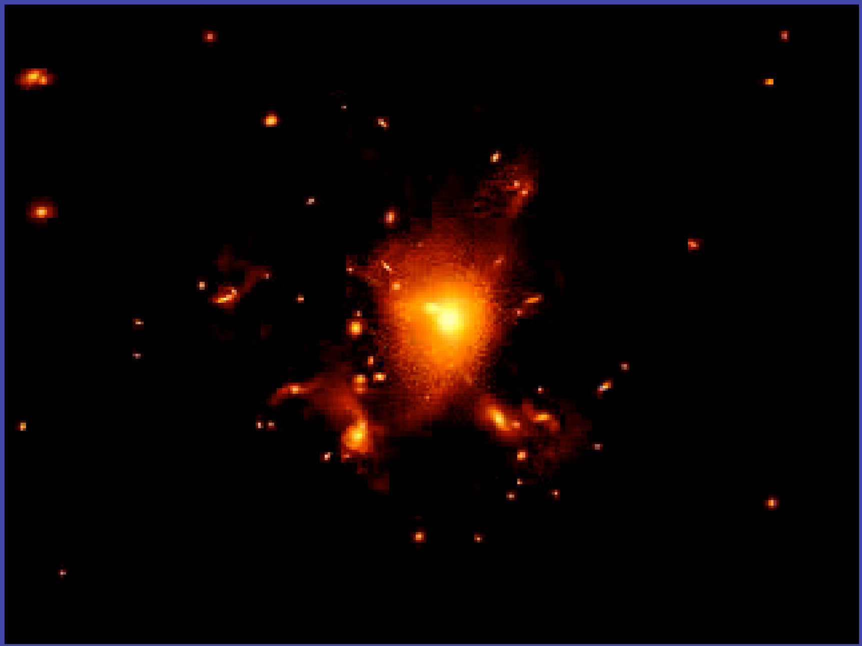
http://www.tomabel.com/

Cluster Formation & Evolution

The evolution of the cluster over 10 billion years

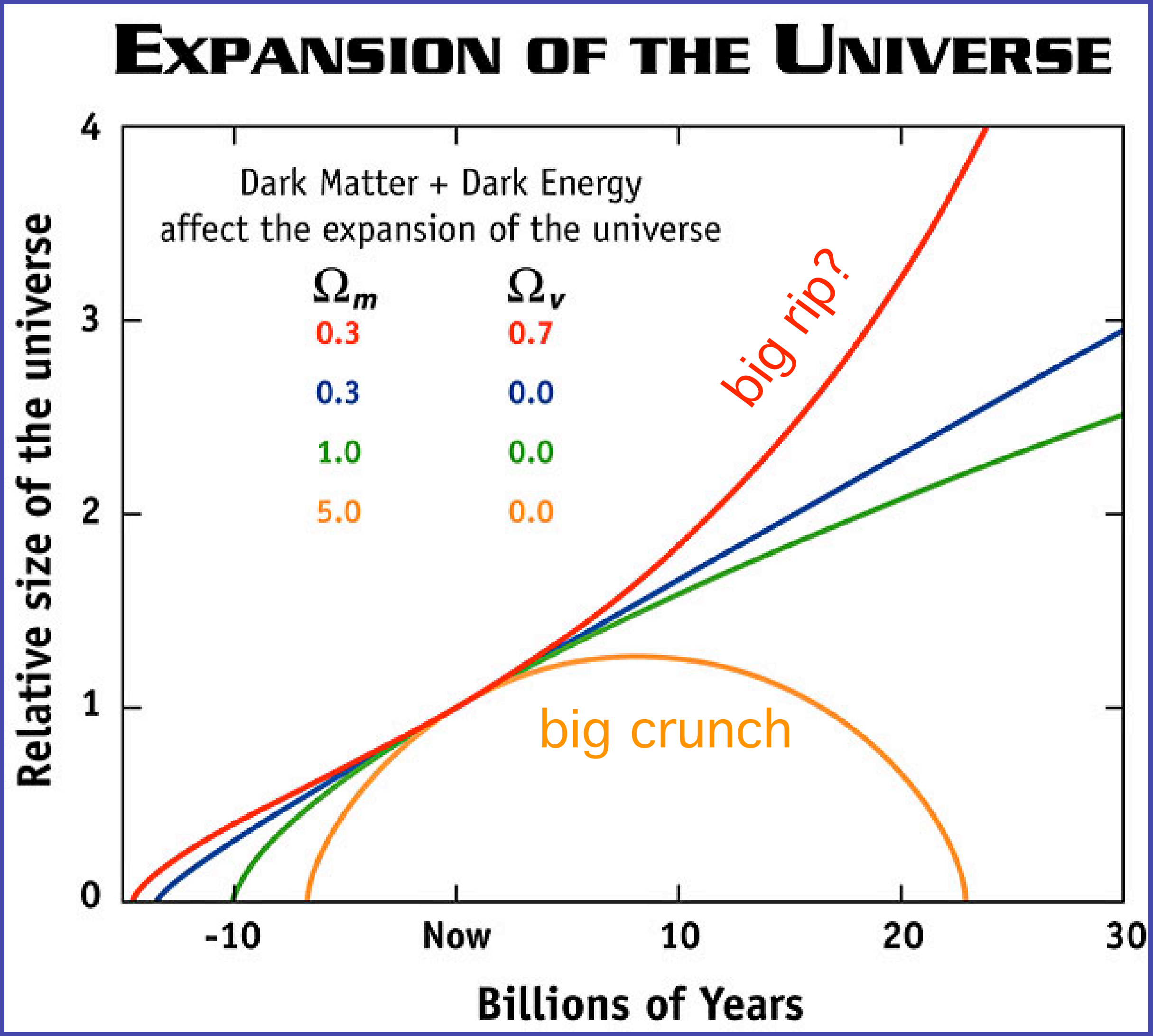


The cluster at z=0.35



John Dubinski
http://www.cita.utoronto.ca/~dubinski/nbody/
http://www.cita.utoronto.ca/~dubinski/bigcluster.html

The Future



Expansion of the Universe
Dark Matter + Dark Energy
affect the expansion of the universe
Ω_m
Ω_v
0.3 0.7
0.3 0.0
1.0 0.0
5.0 0.0
big rip?
big crunch
Relative size of the universe
4
3
2
1
0
-10
Now
10
20
30
Billions of Years

The Big Rip, Big Chill & Big Crunch

The "Big Rip" is the name for cosmologies where the amount of Dark Energy grows so large that it rips everything (superclusters, clusters, galaxies, stars, atoms) apart

The "Big Chill" occurs when the expansion of the universe goes on forever; eventually all sources of heat (stars, black holes) disappear and the universe undergoes "heat death"

The "Big Crunch" occurs when the universe recollapses; Oscillating universe?

Remaining Questions:

There are a number of outstanding questions that cosmologists want to answer:

- Why is the vacuum energy so low but not zero?
- How does the dark energy evolve with time?
- what makes up the dark matter?

Beyond Einstein

NASA's "Beyond Einstein" program should help answer these fundamental question

This program consists of a series of focussed observing facilities:

"Great Observatories": Constellation X (to measure spacetime near black holes and out to large z) and LISA (to detect gravitational radiation)

"Probes": Inflation Probe, Dark Energy Probe and Black Hole Finder

"Vision Missions": Big Bang Observer and Black Hole Imager

http://universe.nasa.gov/

Summary

We apparently live in a Universe filled with dark energy and dark matter and not much else

Rather unsatisfying state of affairs